Robotergestützte ZfP mittels luftgekoppeltem Ultraschall

Armin Huber
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
Zentrum für Leichtbauproduktionstechnologie (ZLP)
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DLR

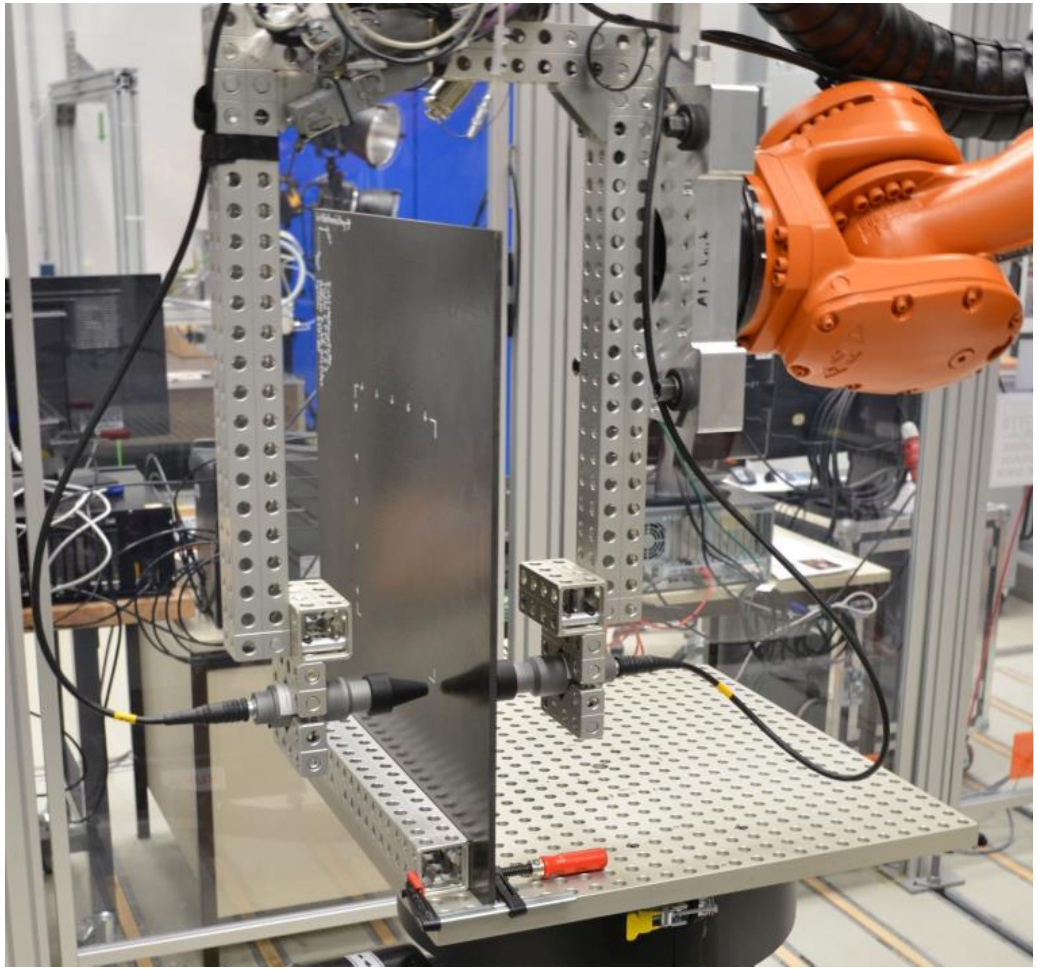
Contents

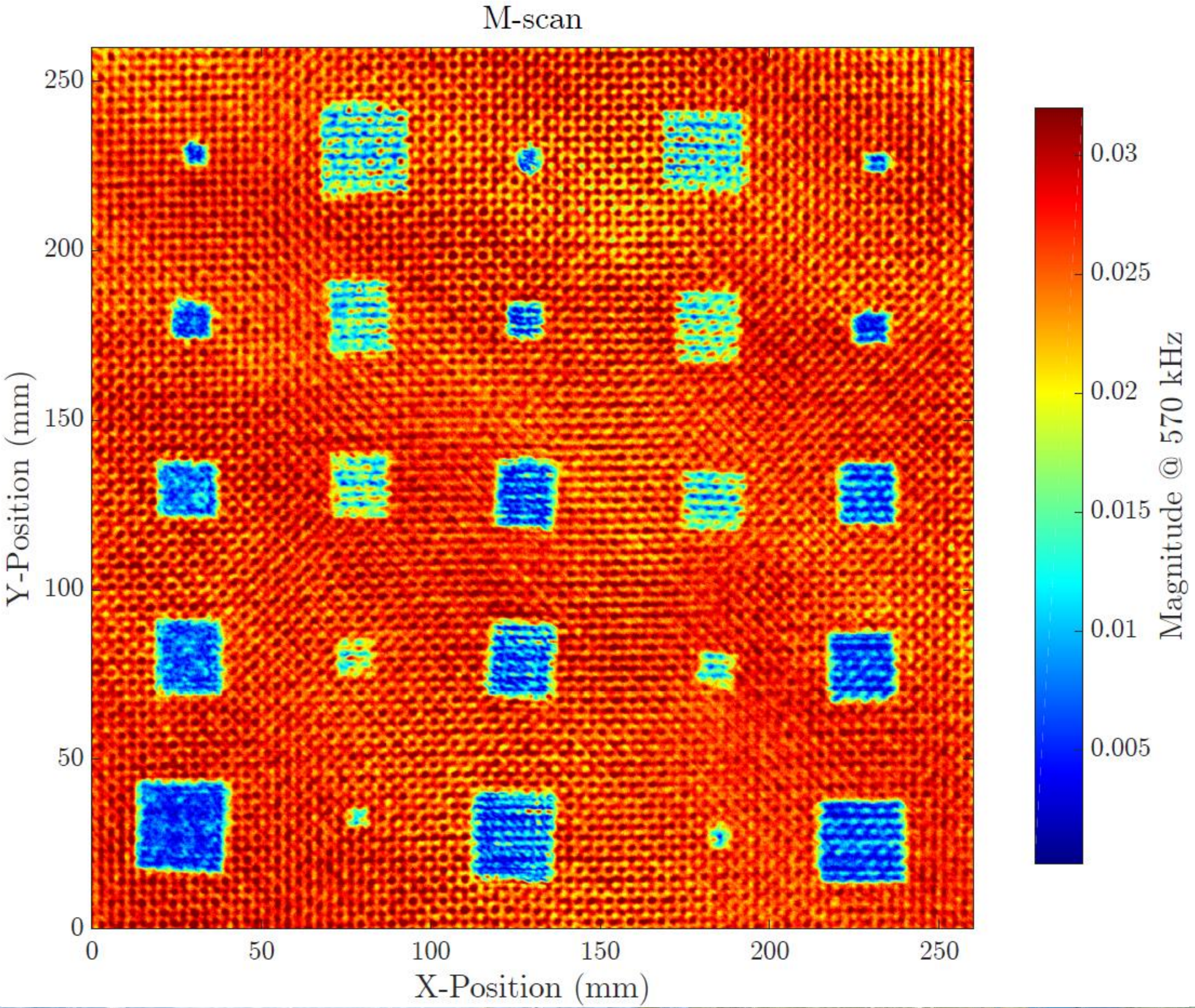
Air-coupled- vs water-coupled ultrasonic testing

Water as couplant:
- Well-proven standard method
- Higher resolution due to shorter wavelengths
- Pulse-echo-technique is possible

Air as couplant:
- Integration into production line possible
- No infrastructure needed like immersion tanks, tubes, water conditioning etc.
- Robots and electrical equipment are not affected by moisture
- No water can infiltrate the CFRP-components or cause corrosion
- Contact pressure and flow rate of coupling medium are non-relevant
- CFRP-components with a high amount of porosity can be inspected, where water-coupled ultrasound gets scattered due its shorter wavelengths

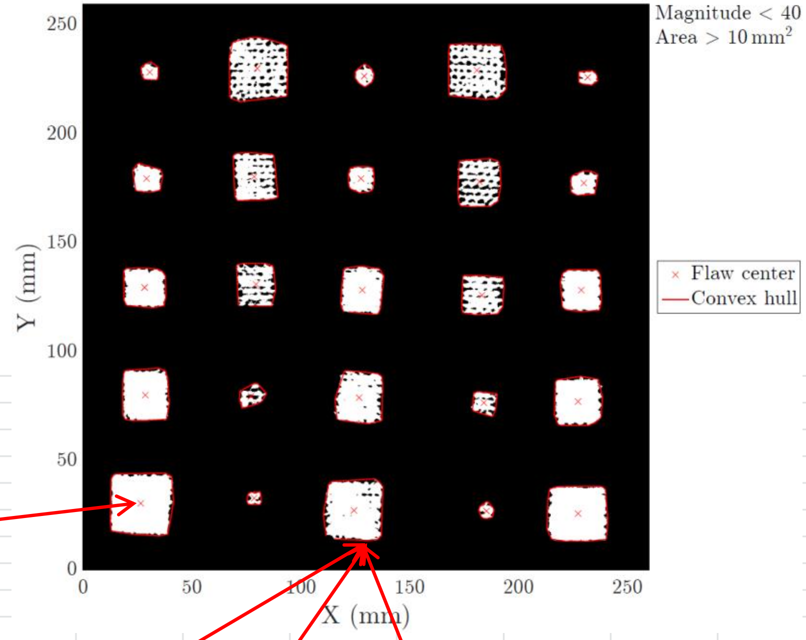
High resolution inspection of reference plate in transmission (NTM)





Evaluation of ultrasonic data

- Performed in MATLAB®
- Export of flaw list

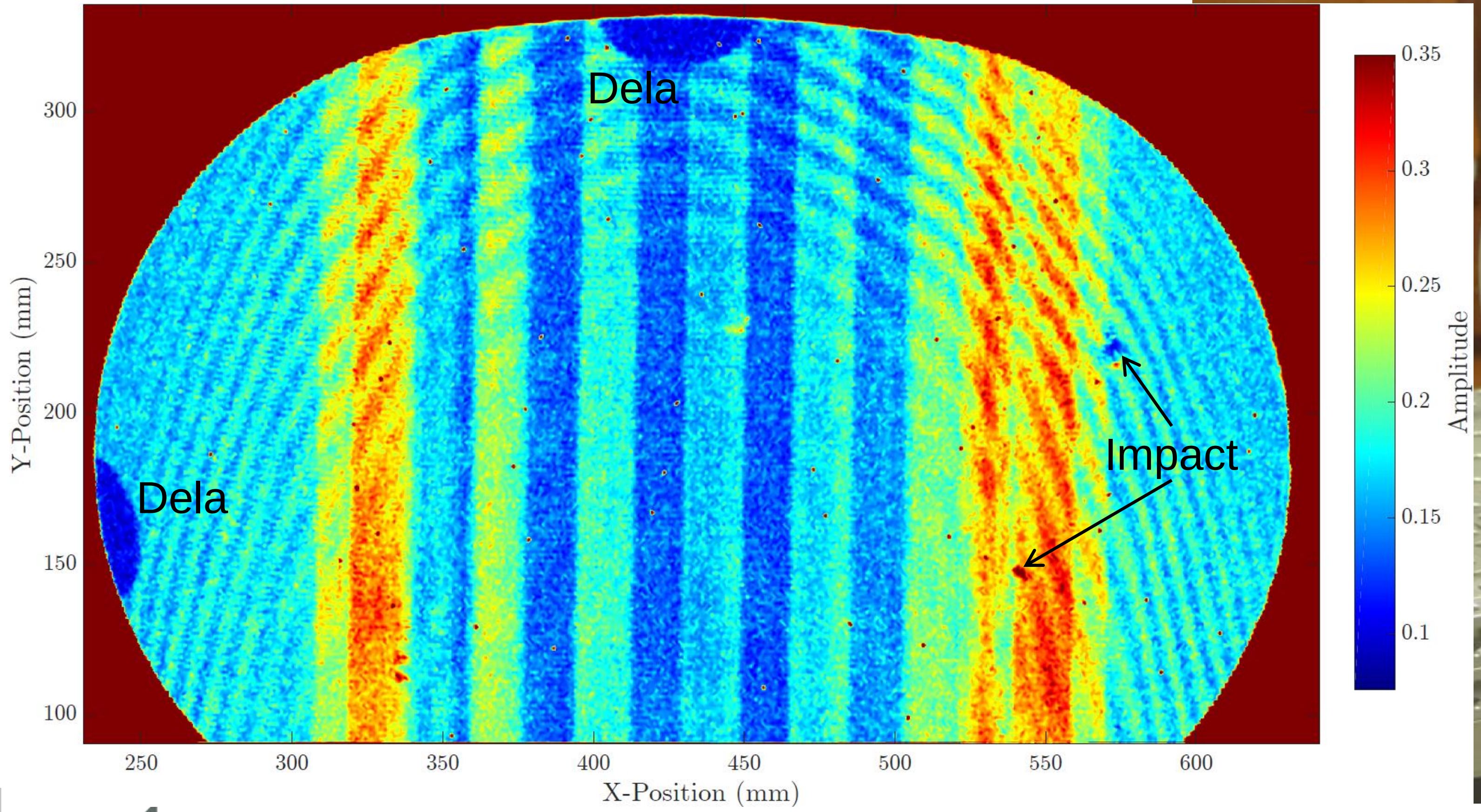


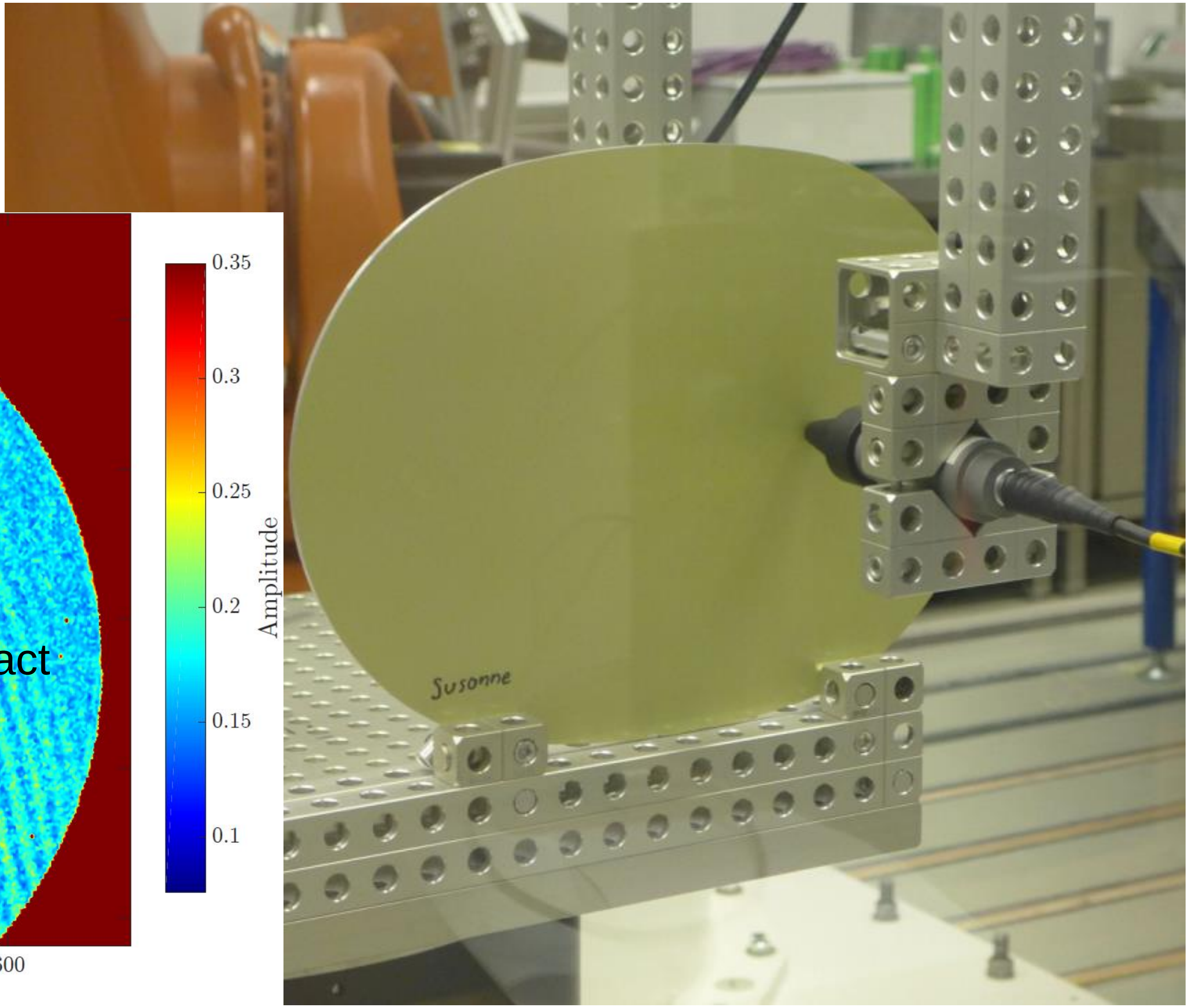
Component	test								
Component	test								
Inspection d	01. Jan 17								
Program	test								
Reference p	X1	X2	X3	Y1	Y2	Y3	Z1	Z2	Z3
Original posi	test								
Current posi	test								

MinGate	MaxGate	PixelSize	Min	Max	MinArea	MinWidth
200	400	1	1	0,25	10	0

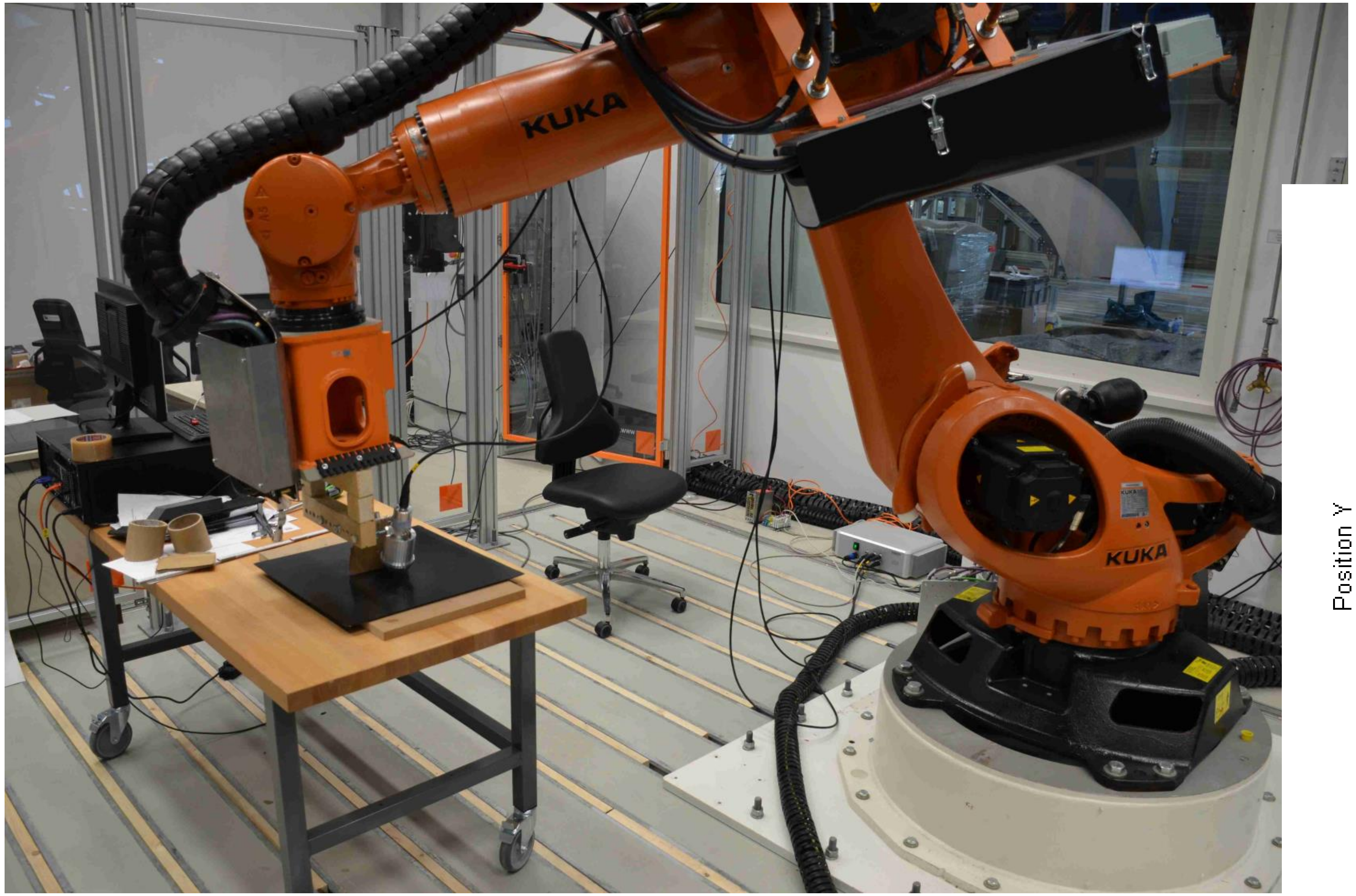
Flaw No	Group No	Flaw label	Flaw type	Flaw middle	Flaw middle	Flaw middle	Length	Width	Area	Min	Max	Average	Median	Std deviatio	Contour type	Point count	X1	Y1	Z1	X2	Y2	Z2	X3
1		Flaw 1		0,003	26,408472	29,0680787	27	27	661	0,08448687	0,31742243	0,17042161	0,17088305	0,03707642	Auto.	20	0,002	15	15,5	0,002	13,5	19	
2		Flaw 2		0,003	28,5075377	78,6005025	20	22	398	0,08735084	0,30739857	0,1699272	0,16706444	0,03934388	Auto.	20	0,003	19	69,5	0,003	18,5	76	
3		Flaw 3		0,003	28,1934307	128,058394	19	17	274	0,10644391	0,3522673	0,18278139	0,18377088	0,03998502	Auto.	20	0,003	20	120,5	0,002	18,5	126	
4		Flaw 4		0,003	29,3181818	178,272727	13	12	110	0,12649165	0,30787589	0,18625732	0,18663484	0,04416621	Auto.	19	0,003	23	175,5	0,003	22,5	176	
5		Flaw 5		0,001	30,4722222	227,861111	7	8	36	0,0902148	0,29976134	0,20827367	0,20906921	0,04700018	Auto.	20	0,003	28	224,5	0,003	27,5	225	
6		Flaw 6		0,005	80,4873418	229,06962	25	28	474	0,09260143	0,34988067	0,20507135	0,20477327	0,04151348	Auto.	20	0,005	71	214,5	0,005	69,5	218	
7		Flaw 7		0,005	79,0459364	179,477032	20	23	283	0,11933174	0,3398568	0,20817865	0,21479714	0,04288817	Auto.	20	0,005	71	169,5	0,005	70,5	170	
8		Flaw 8		0,005	79,2714286	130,004762	16	18	210	0,12792363	0,35465394	0,21048983	0,20811456	0,03959485	Auto.	20	0,005	72	121,5	0,005	71,5	129	
9		Flaw 9		0,005	78,4693878	80,1020408	11	10	49	0,13508353	0,28305489	0,2273635	0,22625298	0,02961758	Auto.	18	0,005	74	74,5	0,005	73,5	75	
10		Flaw 10		0,005	78,1538462	31,0769231	5	6	13	0,20381862	0,22577566	0,21545805	0,21479714	0,00796945	Auto.	16	0,005	76	28,5	0,005	75,5	29	
11		Flaw 11		0,005	124,740418	26,0470383	25	27	574	0,11169451	0,35942721	0,18033812	0,17613365	0,03961675	Auto.	20	0,005	113	14,5	0,005	112,5	15	
12		Flaw 12		0,005	126,744304	78,235443	20	23	395	0,10167064	0,30167064	0,18577928	0,18186158	0,04338332	Auto.	20	0,005	118	68,5	0,005	116,5	71	
13		Flaw 13		0,005	128,230769	126,919872	18	21	312	0,09880668	0,3274463	0,18228689	0,17947494	0,03710682	Auto.	20	0,005	121	117,5	0,005	119,5	120	
14		Flaw 14		0,005	128,081395	178,093023	11	11	86	0,11742243	0,30596659	0,18892712	0,19904535	0,04075573	Auto.	16	0,005	124	173,5	0,005	123,5	174	
15		Flaw 15		0,005	128,861111	224,833333	8	7	36	0,11169451	0,33412888	0,18947229	0,18568019	0,05389236	Auto.	20	0,005	127	221,5	0,005	126,5	222	
16		Flaw 16		0,005	181,070776	228,506849	25	25	438	0,1097852	0,31789976	0,202027	0,20334129	0,03873886	Auto.	20	0,005	170	220,5	0,005	169,5	221	
17		Flaw 17		0,005	181,708738	177,475728	18	19	206	0,1274463	0,31646778	0,21434761	0,22004773	0,0357432	Auto.	20	0,005	176	167,5	0,005	175,5	168	
18		Flaw 18		0,005	183,68617	125,345745	17	17	188	0,12410501	0,28782816	0,20260753	0,20095465	0,03652219	Auto.	20	0,005	177	119,5	0,005	176,5	120	
19		Flaw 19		0,005	183,62069	75,6724138	11	9	58	0,1221957	0,29880668	0,21046004	0,21097852	0,04200661	Auto.	20	0,005	179	72,5	0,005	178,5	73	
20		Flaw 20		0,004	227,001712	24,5136986	27	26	584	0,08878282	0,32649165	0,17436166	0,1699284	0,03551807	Auto.	18	0,005	215	12,5	0,005	214,5	13	
21		Flaw 21		0,004	227,356742	75,8089888	21	21	356	0,09928401	0,32267303	0,1815371	0,17422434	0,04349215	Auto.	20	0,004	218	66,5	0,005	216,5	83	
22		Flaw 22		0,004	228,859779	126,907749	17	18	271	0,09164678	0,31599045	0,16633876	0,16181384	0,03674754	Auto.	20	0,004	222	118,5	0,004	220,5	121	
23		Flaw 23		0,003	230,182796	176,322581	11	10	93	0,12267303	0,32792363	0,18653733	0,17374702	0,05008941	Auto.	20	0,004	226	171,5	0,004	225,5	172	
24		Flaw 24		0,003	231,323529	224,470588	7	6	34	0,14319809	0,27016706	0,20244279	0,19236277	0,04121491	Auto.	20	0,004	229	222,5	0,004	228,5	223	

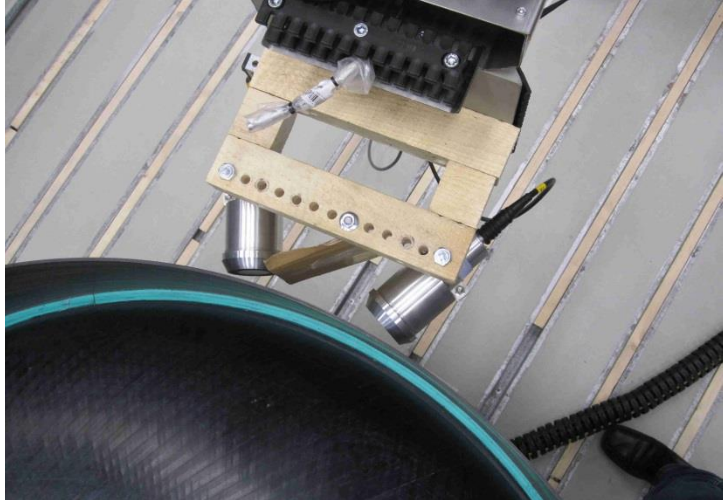
Glare with artificial flaws: Transmission with 570kHz transducers

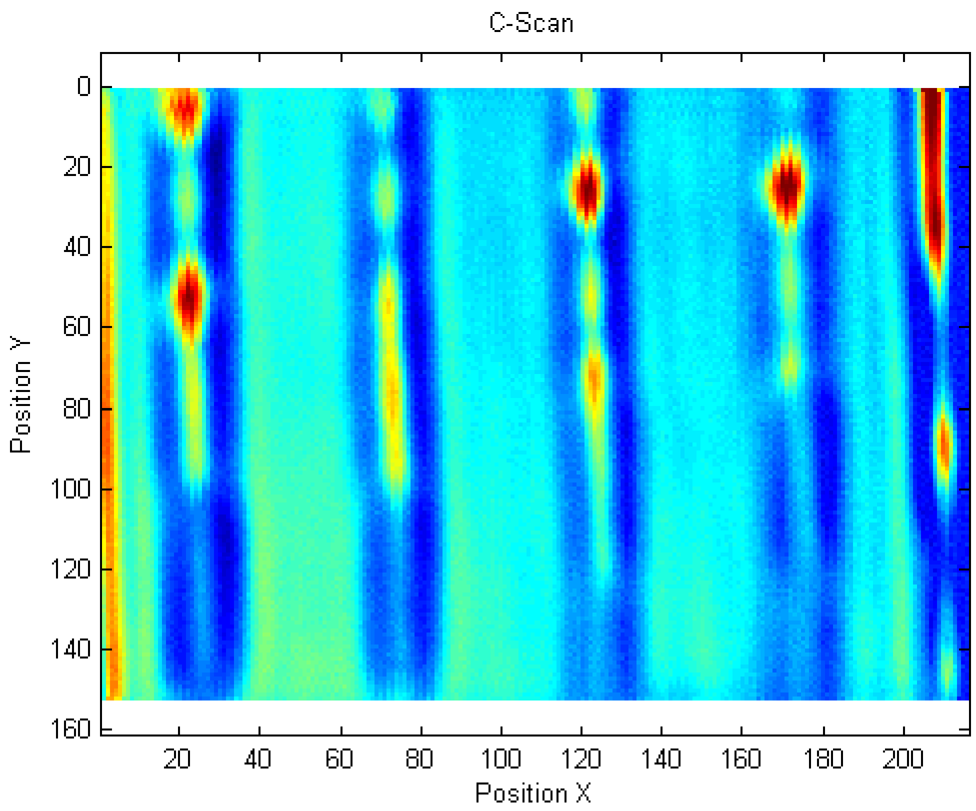




28.1.14: First inspection of a flat plate with artificial flaws at the DLR/ZLP by using Lamb waves (FSRM)







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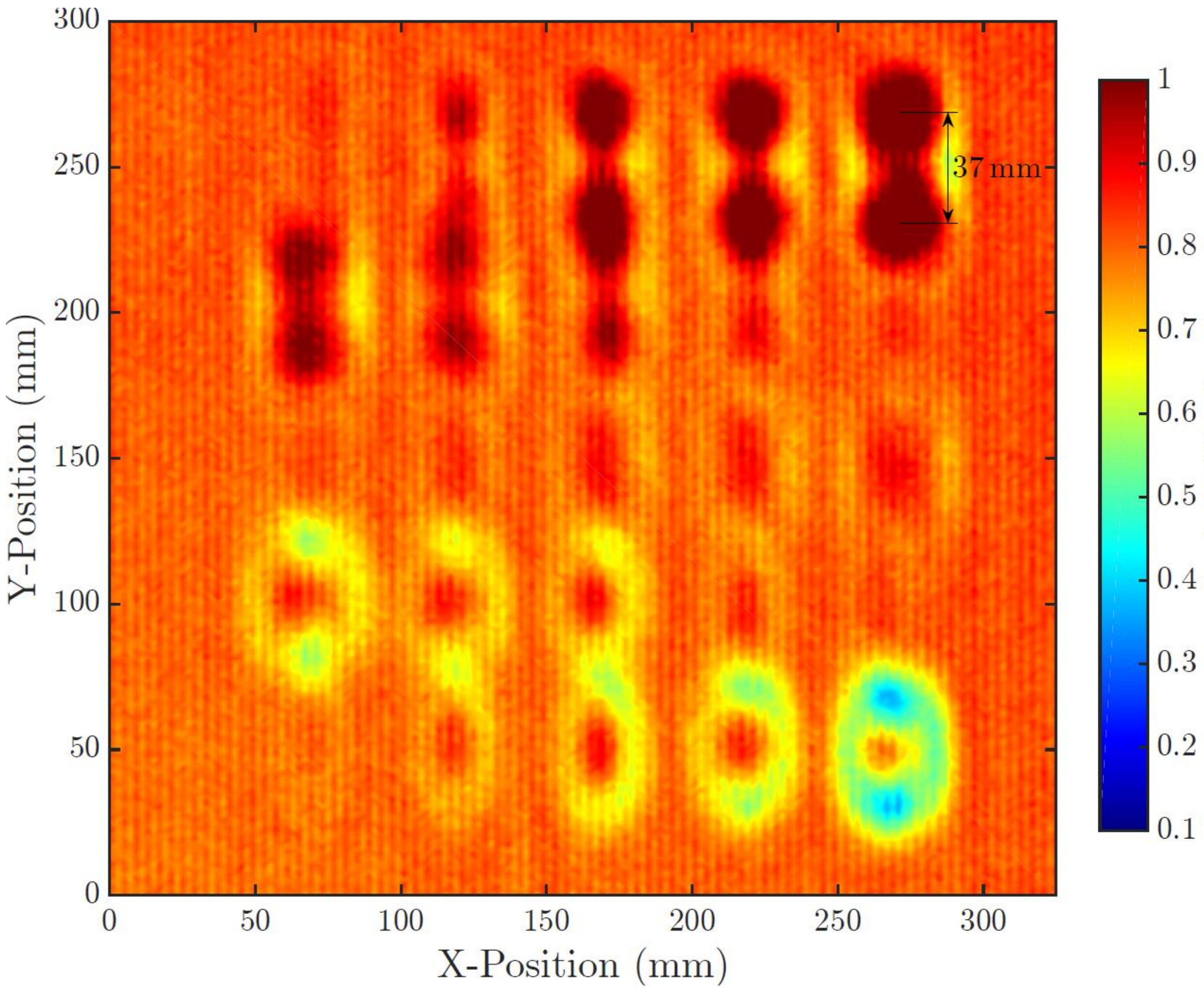
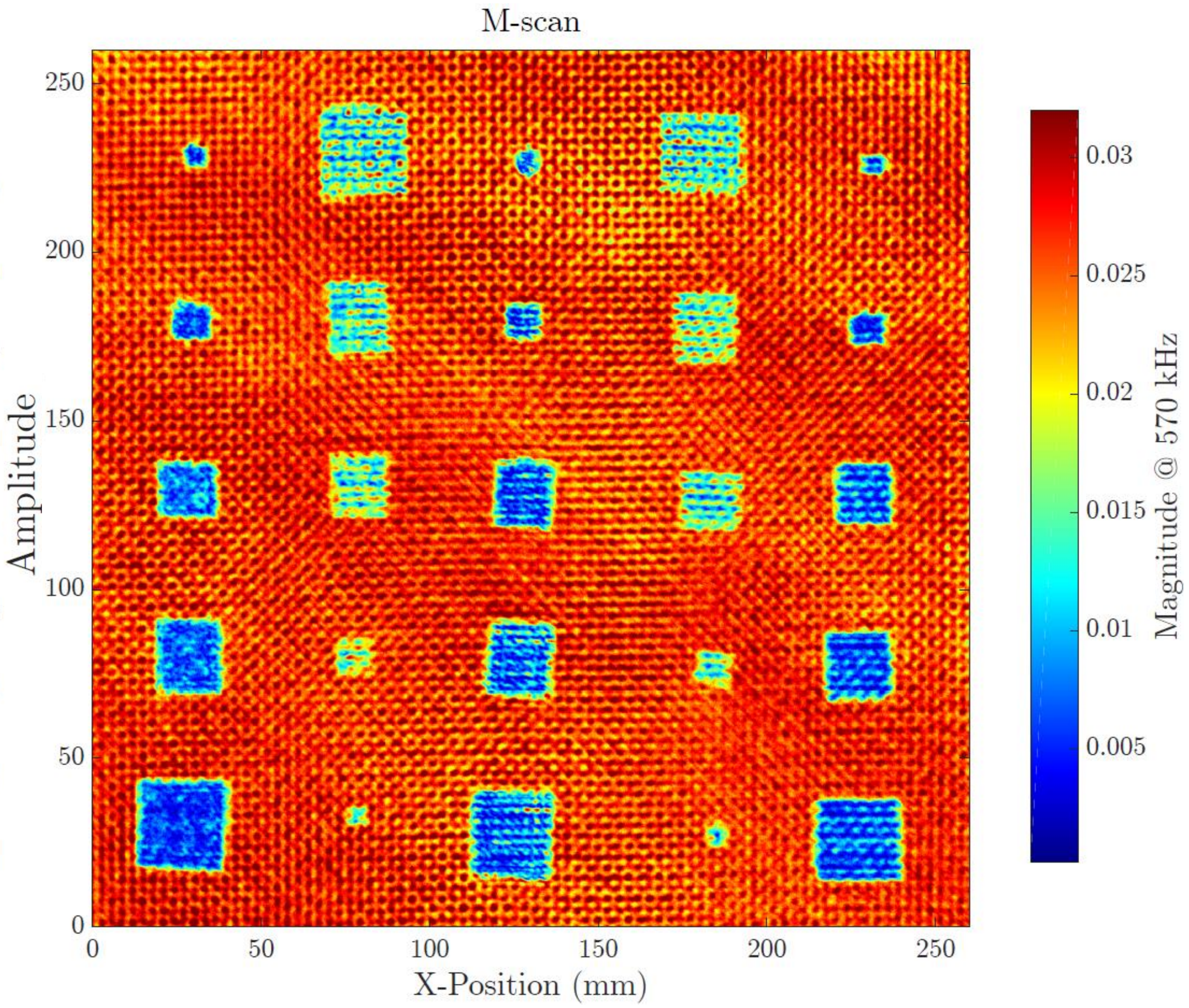
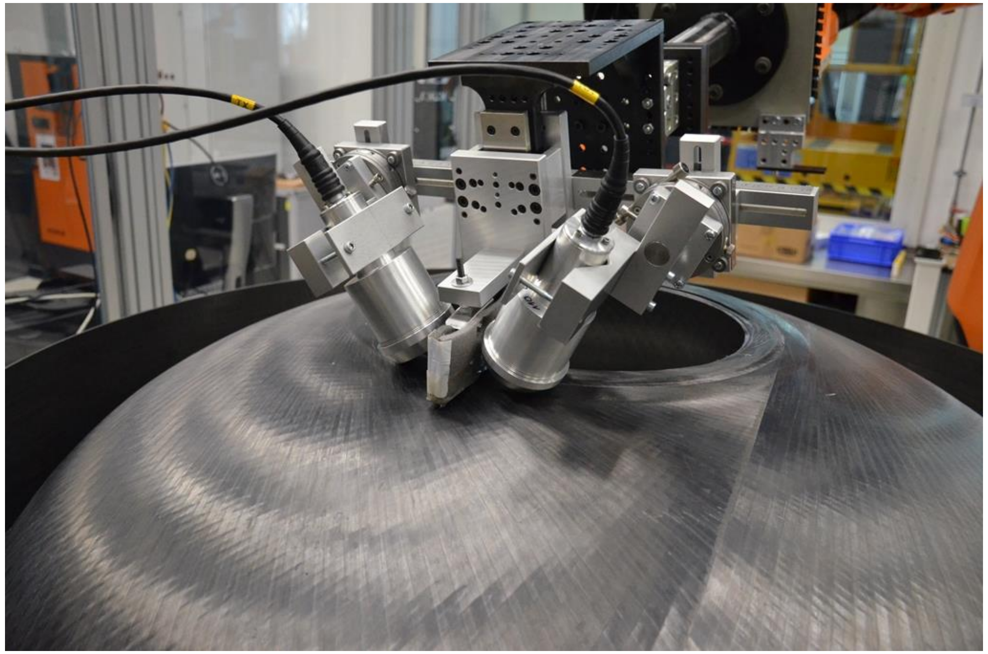
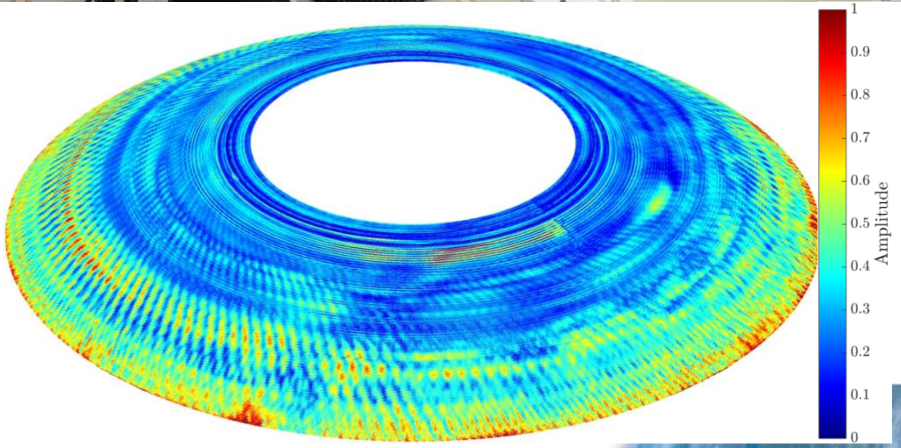
FSRM vs NTM


37 mm
Y-Position (mm)
X-Position (mm)
0
50
100
150
200
250
300
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1


M-scan
Amplitude
X-Position (mm)
Magnitude @ 570 kHz
0
50
100
150
200
250
0.03
0.025
0.02
0.015
0.01
0.005

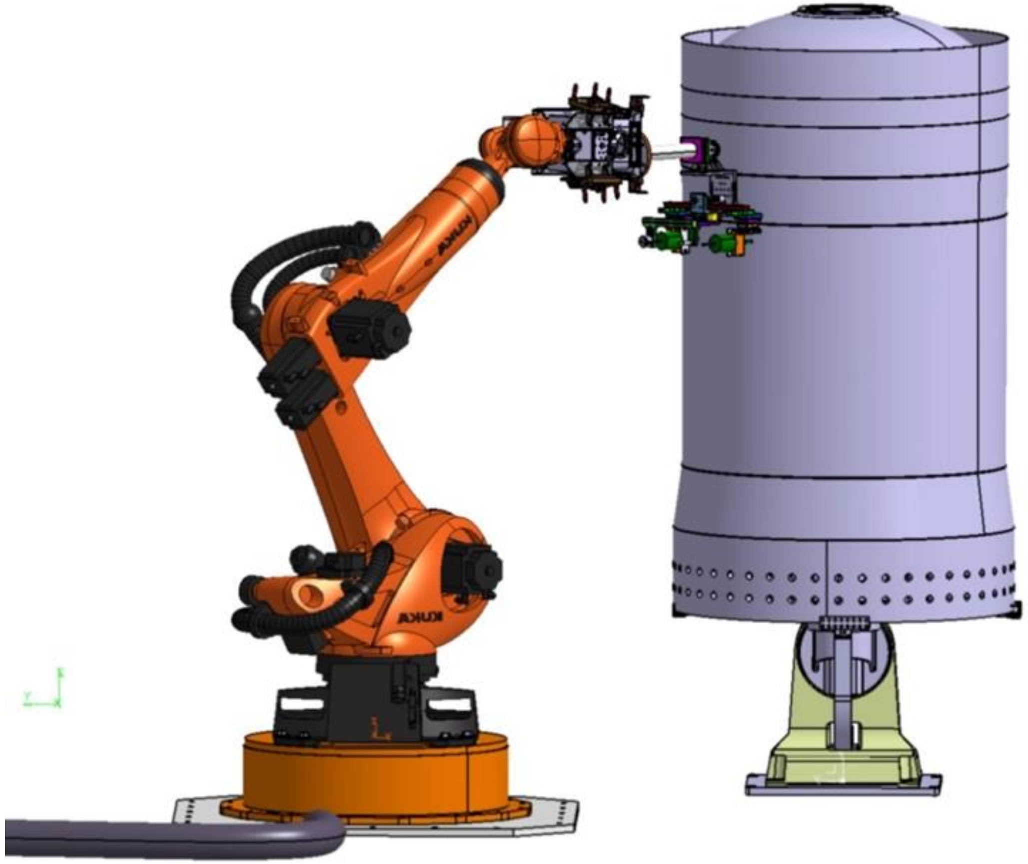
Non-destructive testing on CFRP components through Lamb waves excited by air-coupled ultrasound (ACUT)

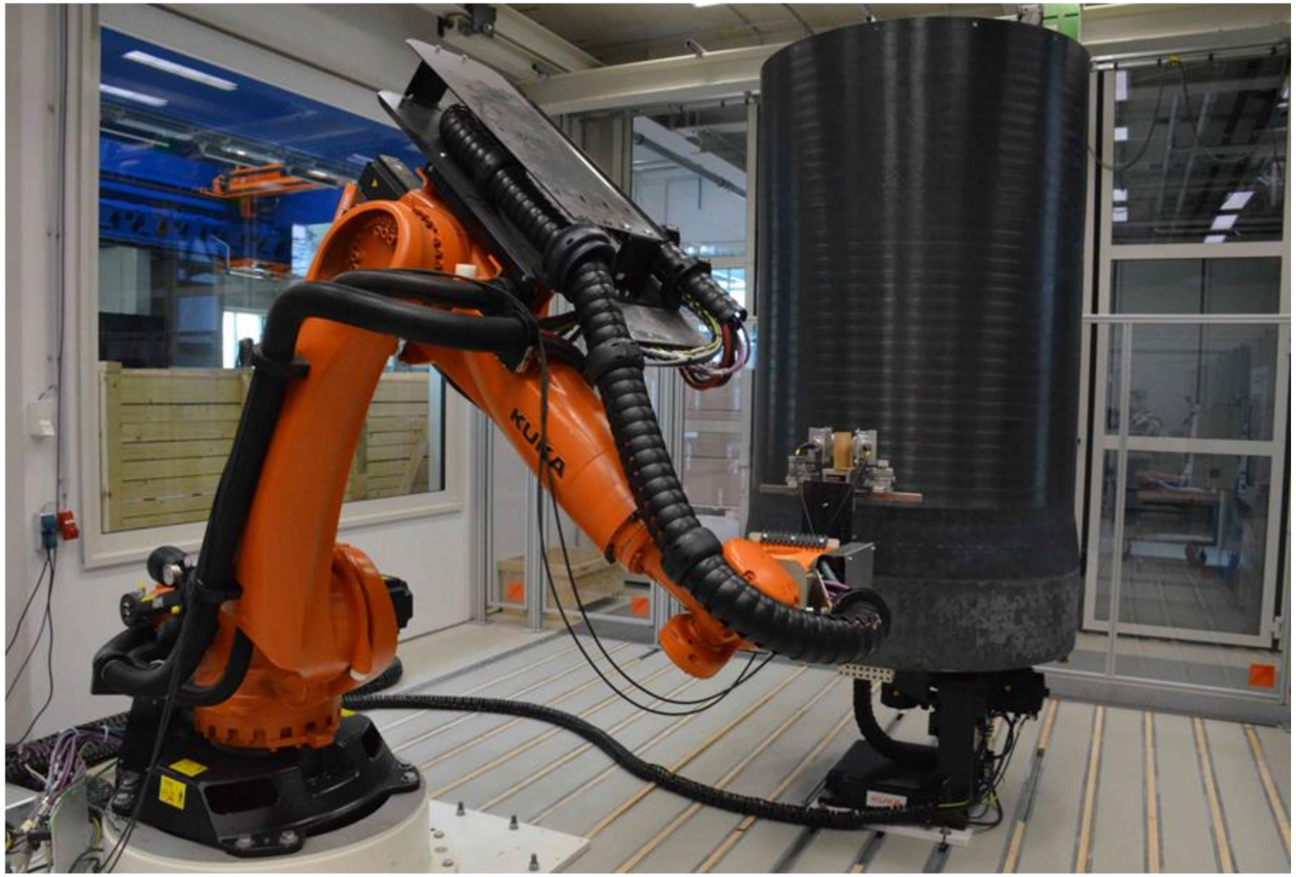


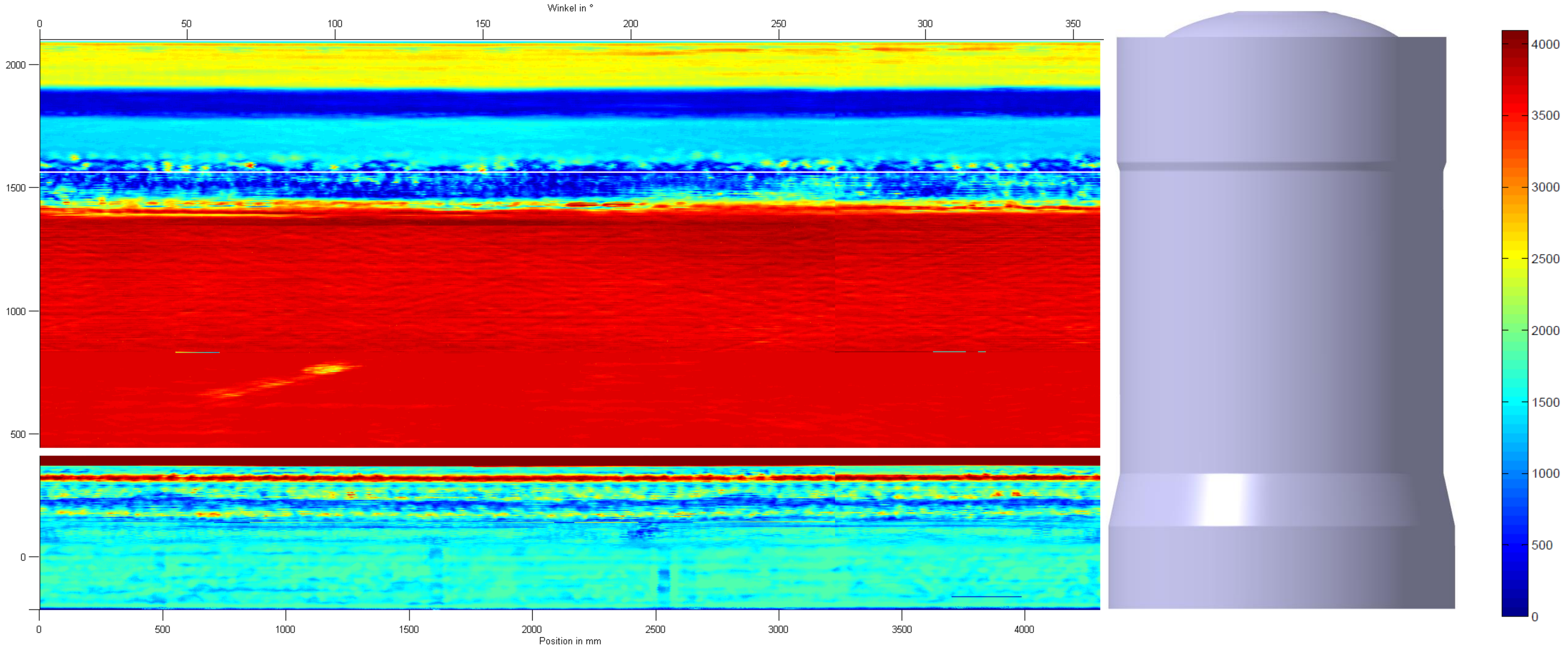


- Single-sided NDT possible by excitation of Lamb waves
- Evaluation of amplitude, time-of-flight, magnitude and phase of Fourier transform

August 2014: Inspection of Versuchsträger from MT-Aerospace/Augsburg (1,4*2,1m)






Winkel in °
0
50
100
150
200
250
300
350
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
3500
4000
Position in mm
4000
3500
3000
2500
2000
1500
1000
500
0

Excitation of Lamb waves

In order to excite Lamb waves, the excitation angle must be adjusted according to Snell's law of refraction:

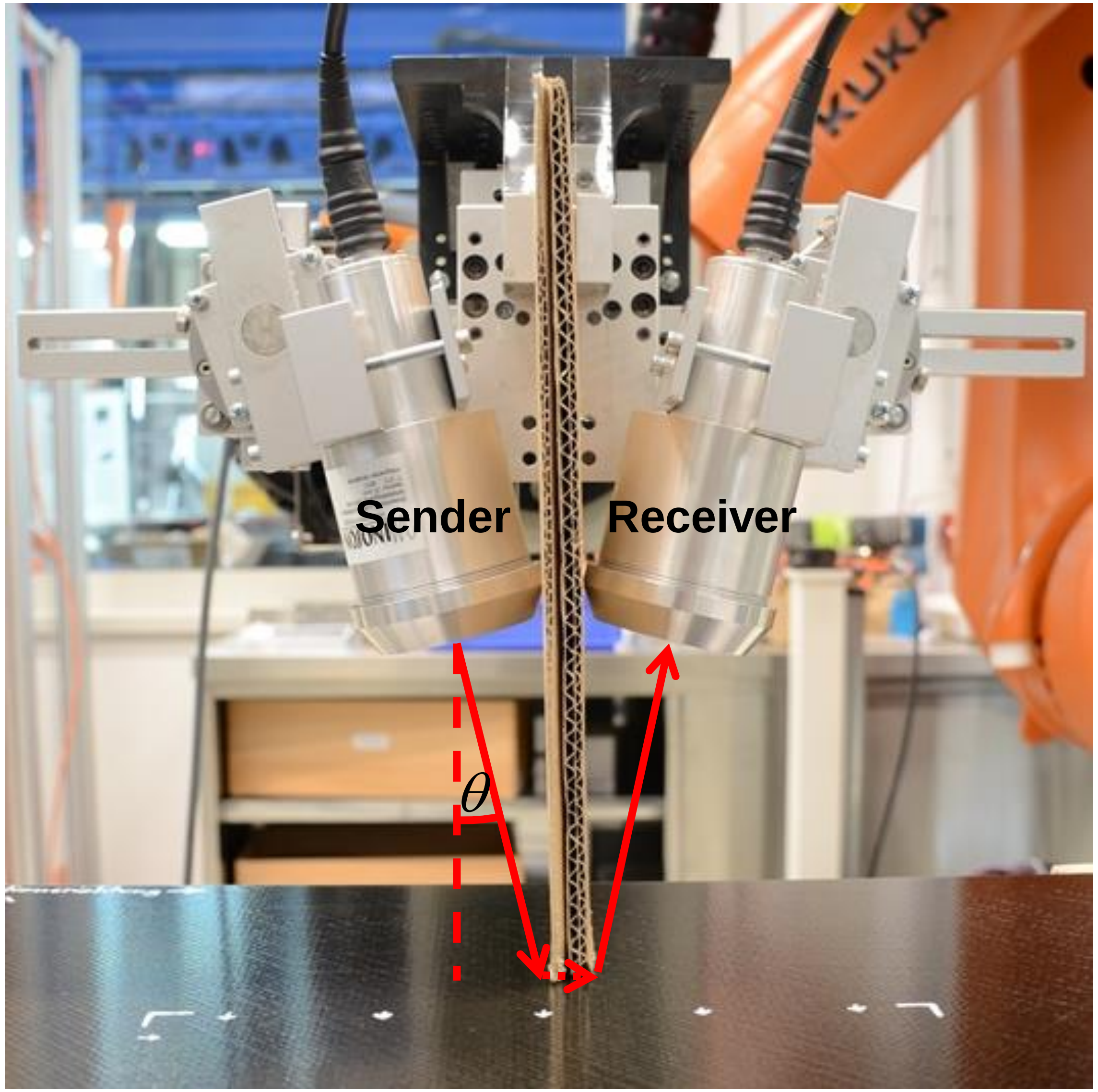
$$\sin\theta = \frac{\lambda_{\mathrm{Air}}}{\lambda_{\mathrm{Lamb}}} = \frac{c_{\mathrm{pAir}}}{c_{\mathrm{pLamb}}}$$

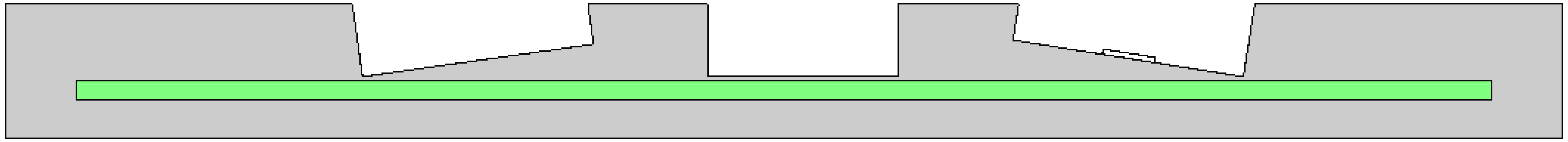
$\lambda_{\mathrm{Air/Lamb}}$ wavelength in air/Lamb wave

$c_{\mathrm{pAir/pLamb}}$ phase velocity in air/Lamb wave

problem: c_{pLamb} unknown

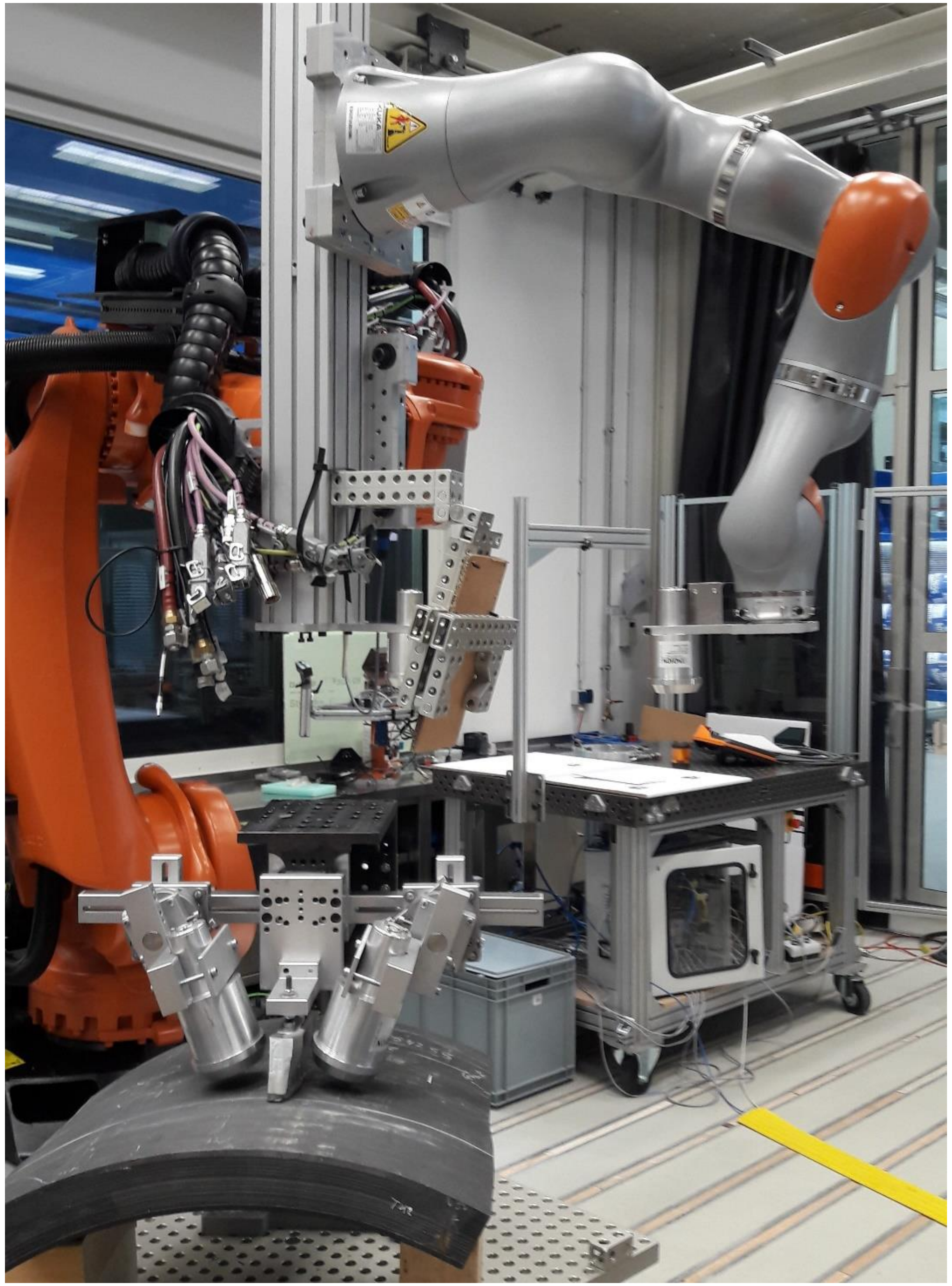
c_{pLamb} depends on layup stiffness and thickness



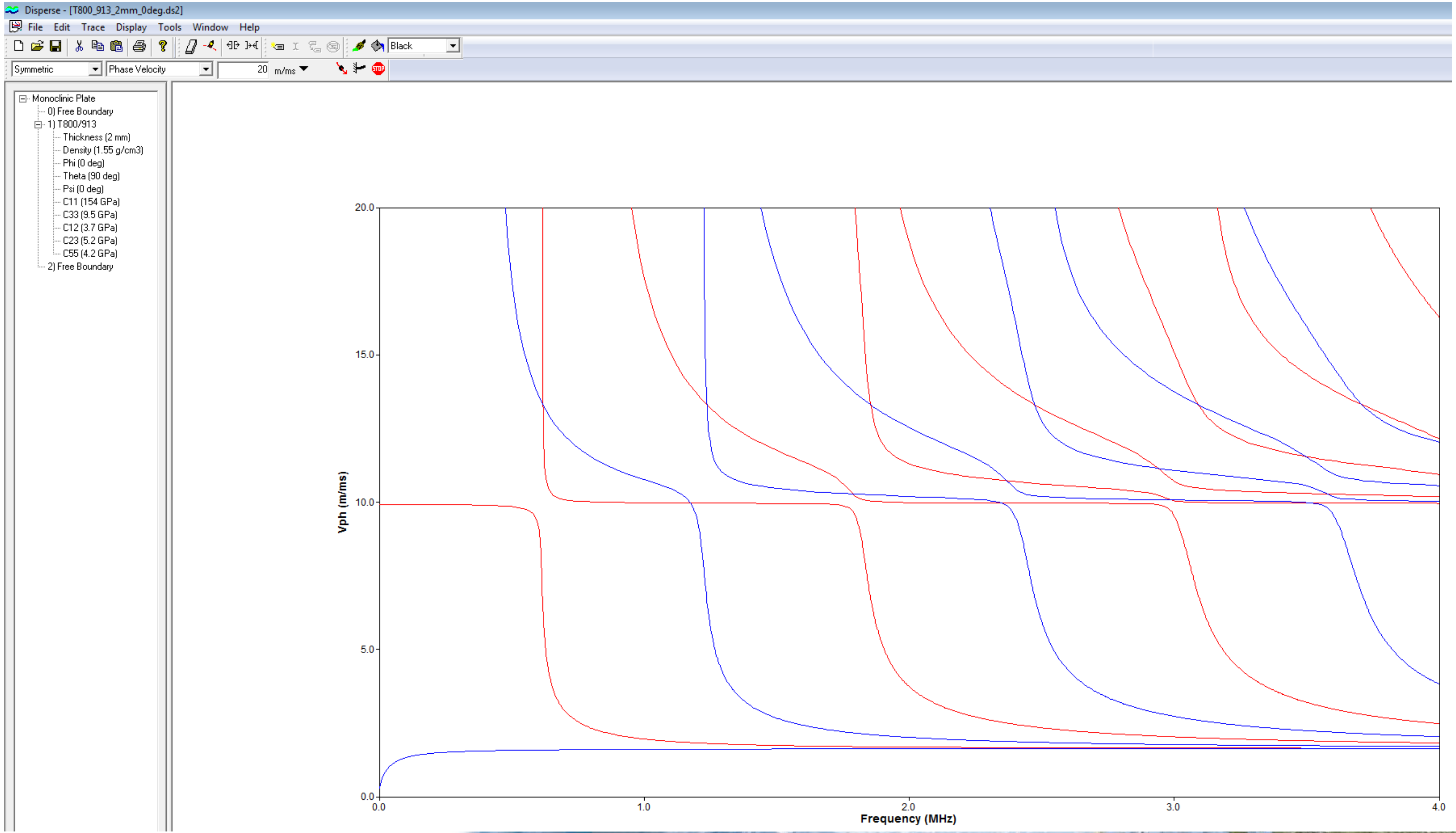


Adaptive end effector

- LBR robot mounted on KUKA KR 270
- Synchronized control
- Calculation of an excitation angle map via MATLAB® „Dispersion Calculator V2“
- Inline adjustment of the excitation angle according to the excitation angle map
- Consistent excitation of Lamb waves
  → improved quality of C-scans



Calculation of Lamb wave dispersion curves with Disperse® software



Problems with Disperse®

- Automatic computation of many layups for excitation angle map EAM impossible
- Impossible to integrate into the software chain for the Adaptive End Effektor (import of layups, export of EAM)
- Excessive dropdown menu clicking
- No optimization for the intended task possible
- **Only 32 (64) layers can be calculated but rocket booster casings can have in excess of 300 layers!**
- **No grouping of layers possible since**
  - **10^2 to 10^5 layups have to be computed**
  - **layups of rocket boosters are highly complicated/irregular**

Own programming of DispersionCalculator in MATLAB®

V1/V1a for single-layered, isotropic media

V2:

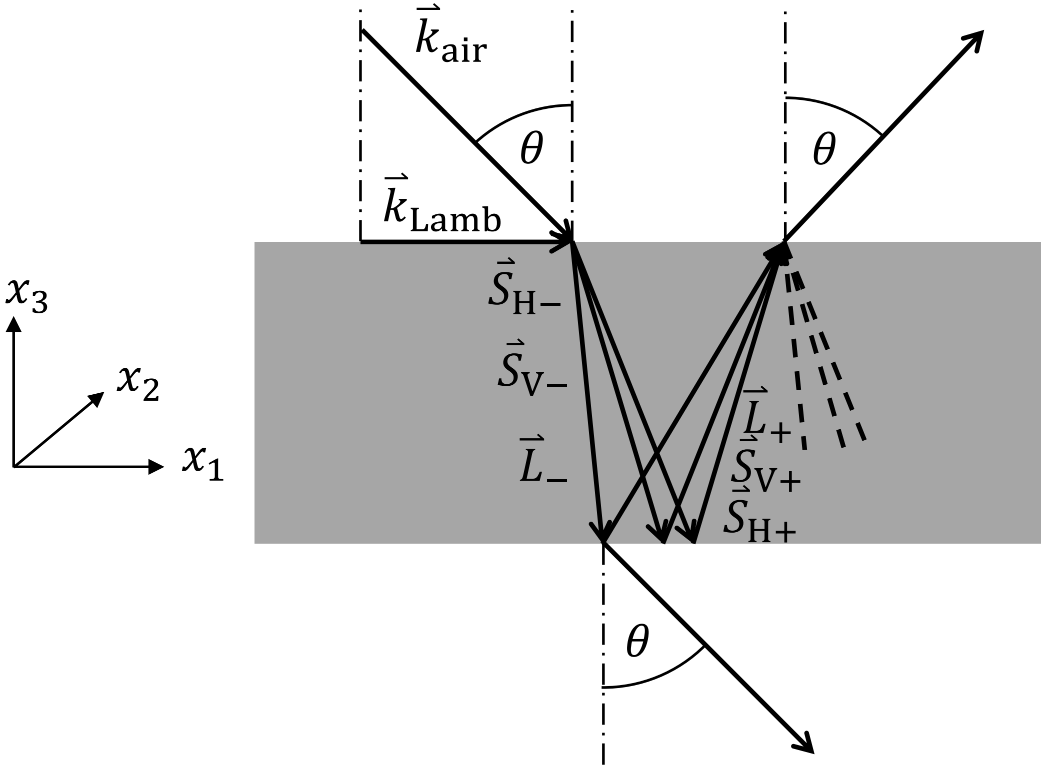
- Computation and plot of dispersion diagrams and more of multilayered, orthotropic media

V2a:

- Import of layups (x_i, y_i, z_i, layer thicknesses$_{ij}$, winding angles$_{ij}$) from Composicad-lookup-tables
- Computation of excitation angles for the A_0-Lamb wave mode at certain frequencies for many layups
- Export of EAM (x_i, y_i, z_i, excitation angle$_i$)

The physics of Lamb waves in anisotropic media part 1/2

A Lamb wave is a superposition of longitudinal and shear bulk waves



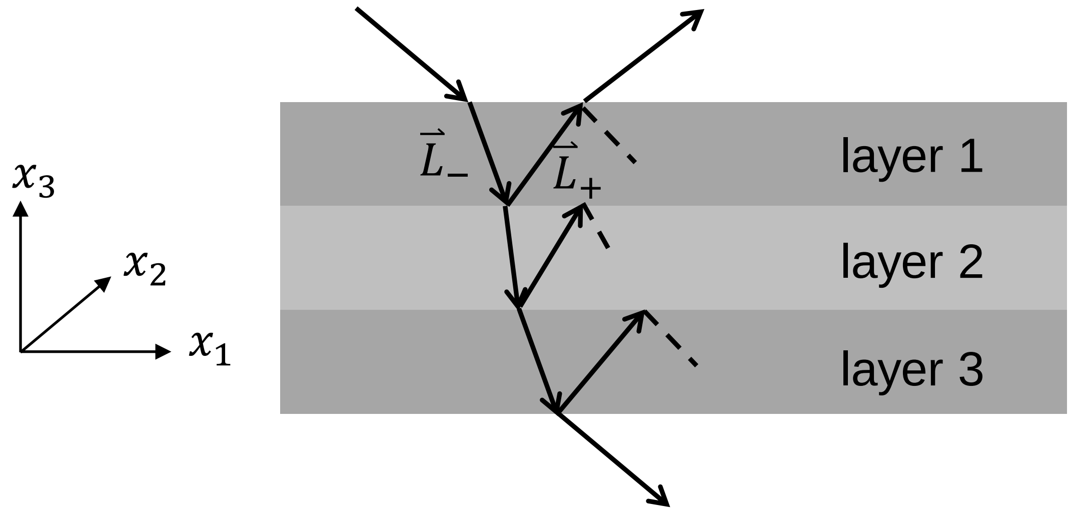
Snell's law of refraction:

$$\boxed{\theta = \sin^{-1}\left(\frac{k_{\mathrm{Lamb}}}{k_{\mathrm{air}}}\right) = \sin^{-1}\left(\frac{v_{\mathrm{air}}}{v_{\mathrm{Lamb}}}\right)} \quad \text{with} \quad k = \frac{\omega}{v_{\mathrm{ph}}}$$

θ	Excitation angle
$\vec{k}_{\mathrm{Lamb}}$	Wave vector of Lamb wave
$\vec{k}_{\mathrm{air}}$	Wave vector of incident wave
v_{Lamb}	Phase velocity of Lamb wave
v_{air}	Phase velocity of incident wave
ω	Angular frequency
v_{ph}	Phase velocity

The physics of Lamb waves in anisotropic media part 2/2

S. I. Rokhlin, L. Wang, "**Stable recursive algorithm for elastic wave propagation in layered anistropic media: Stiffness matrix method**", J. Acoust. Soc. Am., Vol. 112, No.3, Pt. 1, 822-834, Sep. 2002.



$$(u_1, u_2, u_3) = \sum_{q=1}^{6} (1, V_q, W_q) U_{1q} \mathrm{e}^{\mathrm{i}k(x_1+\alpha_q x_3 - vt)}$$

$$(\sigma_{33}, \sigma_{13}, \sigma_{23}) = \sum_{q=1}^{6} \mathrm{i}k(D_{1q}, D_{2q} D_{3q}) U_{1q} \mathrm{e}^{\mathrm{i}k(x_1+\alpha_q x_3 - vt)}$$

$$\begin{vmatrix} \sigma_{33} \\ \sigma_{13} \\ \sigma_{23} \\ \sigma^*_{33} \\ \sigma^*_{13} \\ \sigma^*_{23} \end{vmatrix} = \begin{vmatrix} \text{Stiffness-matrix} \\ K(6 \times 6) \end{vmatrix} \begin{vmatrix} u_1 \\ u_2 \\ u_3 \\ u^*_1 \\ u^*_2 \\ u^*_3 \end{vmatrix}$$

Condition for free waves: $\sigma_{ij}, \sigma^*_{ij} = 0$

Non-trivial solution if $\det(K) = 0$

σ_{ij}/u_i Stress/displacement field quantities at the top… σ^*_{ij}/u^*_i …at the bottom of the plate